Renewable and Sustainable Energy Reviews 16 (2012) 4500–4507

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: Case study

Mohammad Al-Smairan *

Energy Research Center, Al al-Bayt University, Mafraq, Jordan

ARTICLE INFO

Article history:
Received 19 March 2012
Received in revised form
12 April 2012
Accepted 18 April 2012
Available online 26 June 2012

Keywords:
Photovoltaic
Jordan Badia
Diesel engines
Remote areas
Present value cost

ABSTRACT

The availability of water and the ability to access are the key questions arising in developing countries including Jordan, which is the fourth poorest country in the world regarding water resources. Renewable energy, especially solar energy, can potentially play a role in the supply of safe water in Jordan Badia, where nearly 80% of the total area of Jordan is Badia, and in most cases these deep wells are far away from the national grid electricity, and in some of these areas there is an important quantity of groundwater at shallow depths. This paper introduces and compares the cost-effectiveness and the Present Value Cost (PVC) for the economic evaluation of power supply for pumping systems in remote areas in Northern Badia of Jordan by two different energy supply systems, photovoltaic systems and diesel engines.

Many variables are taken into account such as the fuel prices, and the required investments. The comparison is made for a wide range of variable values, total head, tank capacity, photovoltaic array peak power and pumping requirements. A case study in Tall Hassan station is conducted to analyze the two power supply pumping systems, which are designed to supply drinking water.

The results obtained are useful for choosing the best alternative for the power supply of pumping systems in wells in Northern Badia of Jordan.

Contents

1. Introduction

Jordan lies in the Middle East within latitude 29°11 to 36° north and longitude 34°59 to 39° east. It is a small country with a total area of 89,206 km. Jordan is comprised of several different geographical areas with special features. It provides a diverse landscape, from hills and mountains, like the area surrounding the Dead sea that is 400 m below sea level (bsl). There are steep valleys like the Jordan valley to the fertile areas in the north of the country, and there is a desert, which is called as the Badia plains that extend in an eastward direction into Saudi Arabia. The largest part of Jordan is classified as arid and semi-arid land known as

* Tel.: +962 2 6297000x2501; fax: +962 2 6297089.
E-mail address: wesam93@yahoo.com

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.04.033

Badia. Badia is a classical Arabic word used to describe arid to semi-arid regions of the Middle East, where rainfall averages less than 200 mm, which today makes up part of Jordan, Syria, Saudi Arabia and Iraq [1].

This region lies in the eastern part of the country, from north to south and covers an area of 72,660 km^2 (80%) of the country's total area. Desertification is a common fear, which threatens that region, causing degradation of resources and most painfully demographic displacement. It has an arid climate, harsh weather conditions and little natural vegetation, which have naturally limited the Badia population to only about 5% of the country's population. This has consequently limited the presence of services such as electricity and cold water [1,2].

Energy and safe drinking water, two indispensable inputs to human existence, are scarce resources for the people in Jordan Badia. Fresh water is the primary source of life for the mankind and one of the most basic necessities for rural development. In many developing countries like Jordan, the inadequate supply of drinking and irrigation water is a serious problem [3,4]. The remote and rural demand of water for crop irrigation, watering sheep and domestic water supplies is increasing each year and at the same time, rainfall is decreasing annually in Jordan Badia and therefore, desertification has increased. So, surface water is becoming scarce and groundwater seems to be the only alternative in this area [4]. Water wells are essential for the people living in the Jordan Badia and as a result of the existence of the bacterial contaminants in the surface water, remote and rural people have been using underground water [3,5].

Diesel pumps have traditionally been used to pump water. However, photovoltaic array and wind turbine pumps are now competitive in the market and are rapidly becoming more attractive than the traditional power sources. Solar and wind energy sources are especially useful in remote areas where diesel generator engines are inherently noisy and expensive to run, especially for consumers in rural areas where fuel delivery costs may be high. Also, installing diesel generators in these remote areas is restricted for many reasons. Fuel buying around the year, and operation and maintenance of these generators are the most significant factors against the economic deployment of diesel generators [4,6,7].

In remote and rural areas in Jordan with no access to grid power, water authorities and private farmers have to rely on diesel engines and photovoltaic systems for pumping water from the water wells [3,4].

Bhave [8] shows that, solar water pumping systems are suitable for drinking water and minor irrigation applications in areas where cheaper sources of energy are not readily available. Kelley Leah et al. [9] stated that solar water pumping systems are an attractive application of renewable energy technology. The results suggest that photovoltaic water pumping systems are technically and economically feasible. Technical feasibility is determined from the maximum power required for pumping water and economic feasibility is determined by comparing present value cost of the photovoltaic and diesel pumping systems. Also, the results of this study suggest that the price of the diesel fuel has increased within the last 10 years to make the photovoltaic water pumping systems economically feasible, despite the initial costs of photovoltaic systems. As the price of the solar panels decreases, the capital costs will decrease, making photovoltaic systems even more economically attractive.

Kala et al. [10] stated that distribution line extension costs can run from US$ 10,000 to US$ 16,000/km, thereby making the availability of electricity to small water pumping projects economically unattractive. Photovoltaic water pumping has several advantages over traditional systems; for example, diesel or propane engines not only require expensive fuels, but also create noise and air pollution in many remote pristine areas. Solar systems are environmentally friendly, low maintenance, and have no fuel cost. Also, this paper presents technical, environmental, and economic benefits of the photovoltaic water pumping systems compared to stand alone generator and electric utility. Hamidat and Benyoucey [11] mentioned that, because of the current high crude oil price, the photovoltaic water pumping systems are still the best adopted energy resource to supply drinking water in remote, isolated and scattered villages. Kumar and Kandpal Tara [12] conducted a study for estimating the utilization potential of solar photovoltaic, wind, gas and fuel engine and biogas for pumping water in India. The results show that the solar photovoltaic water pumping systems have the maximum utilization potential in India. Hrayshat Eyad and Al-Soud Mohammad [13] show in their paper that using solar energy development for pumping water in Jordan is more attractive than diesel generator in Jordan Badia, where the fuel prices have increased over the last few years. A study carried out by Ramos and Ramos Helena [14], for using solar energy for powered pumps to supply water for rural or isolated zones: a case study, indicated that the water cost obtained is believed to be a competitive value proving these types of solutions as good alternatives to extend the electric grid or having a diesel generator. Butcher [15] discussed in his study the issue of economics on the basis of comparison between the photovoltaic and conventional fossil fuel powered systems. Inspite of high investment costs as the most important limiting factor for more widespread application, an increasing number of photovoltaic water pumping systems have been installed and operated successfully in many countries, where the solar radiation is high. A study published in the international renewable energy congress in Tunisia carried out by Mahjoubi et al. [16] shows that the life cycle cost of the diesel generator system is higher than that of the photovoltaic system for pumping water in the desert climate of Tunisia, which completely agrees with the results obtained in this study for desert climate in Jordan. The total net present cost of the photovoltaic water pumping system is less than that for diesel engine pumping system as shown by Abu-Aligah [17] during a study carried out in Jordan as a comparison between the two systems for pumping water. Also, in an article by Eker [18] it is mentioned that since the increase in price with an increase in per unit power output of a photovoltaic system is greater than that for a diesel, gasoline or electric system, photovoltaic power is more cost competitive for pumping water and when compared with traditional energy sources for small and remote applications. A life cycle cost analysis for photovoltaic and diesel engine water pumping systems in Mexico done by Foster et al. [19] shows that the photovoltaic systems are generally competitive for water pumping applications and additional benefits such as the elimination of potential well contamination and health risks from hydrocarbon fuels are not included here and are difficult to reflect in conventional life cycle cost economic analysis. Kordab [20] has studied the priority option of photovoltaic systems for water pumping in rural areas in ESCWA member countries, among which one of them is Jordan; he found that the opportunity for competition between photovoltaic systems and other alternative systems depends on the price level that photovoltaic systems can achieve. The photovoltaic systems are competent with other options when the total cost of the photovoltaic system is less or equal to 5 US$/Wp. Nowadays, most of the photovoltaic system types costs are less than 5 US$/Wp.

Solar radiation in Jordan Badia is one of the best in the Middle East. Photovoltaic systems are commonly used for stand-alone applications and are commercially available with sizes in the range from less than 1 kW up to several hundred kW [5]. Solar energy is one of the potential renewable energy sources, which is being harnessed in a commercial scale today. Solar energy is a non-depletable, non-polluting source with low operating cost,

high reliability and cost free in its original radiation form. They require minimal maintenance and are well suited for remote and rural locations [5,21–24]. With regard to the connection to the electrical network, photovoltaic systems have several advantages. They can be located close to the demands so distribution and transmission costs and consequently energy and capacity losses are reduced. The main disadvantage of photovoltaic systems is the high initial cost, but the drop in prices of the photovoltaic modules, as a result of the high level of development of the photovoltaic sector, makes the economic viability of the photovoltaic installations possible. Therefore, solar energy will represent a suitable solution for energy requirements especially in rural areas [5].

The aim of this paper is to examine the best application of two power supply systems for pumping water from a deep well in Tall Hassan station in the northern east part of Jordan Badia, and also for considering the present value cost and the cost of water produced for the two different systems.

2. Tall Hassan station

2.1. General information

Tall Hassan station is located in the northeast Badia of Jordan, near the main road to Iraq, 15 km from Azraq town, with latitude about 400 m above the sea level. The station was built in 1989 as part of a scientific agreement between the Higher Council of Education in Iraq and the Royal Scientific Society in Jordan. The station has an area of 50,000 m^2 cultivated with many trees. Tall Hassan renewable energy station has been established for the purposes of research, development and training in the fields of new and renewable energy, raising the efficiency of using energy in different rehabilitation projects. The station is now used as an experimental site for researchers who want to conduct research on renewable energy. Also, several projects on rangeland improvement in the area depend on water supplied by this station. The area surrounded by the station is targeted for many nomadic Bedouin and their sheep and goats depending on the water supplied by the station for domestic uses and watering their sheep and goats. Therefore, this station is one of the most important ones in Jordan Badia on which nomadic Bedouin depends for their water purposes especially in the summer months.

2.2. Climate and hydrological data of the site

The climate data of the site under consideration are as follows [25]:

Average wind speed = 4.65 m/s.
Average daily solar radiation = 5.7 kWh/m^2/day.
Average yearly temperature for reference year = 19° C.
Average relative humidity = 40.5%.

While the hydrological data of the groundwater well are [25] as follows:

Well depth = 174 m.
Static water level = 69.55 m.
Dynamic water level = 81.72 m.
Well productivity = 106 m^3/h.
Design criteria = 45 m^3/day.
Pumping head = 105 m.
Salinity = 717 ppm.

Fig. 1. Photovoltaic water pumping system in Tall Hassan station, North Badia, Jordan.

3. Photovoltaic water pumping system

At present, photovoltaic water pumps systems are widely used in Jordan Badia as well as many other countries or regions with available solar radiation. Solar pumps have proven to be a cost effective and dependable method for pumping water in regions where water resources are spread over long distances, grid lines are not available and fuel and maintenance costs for diesel generators are high [26].

Water pumping for irrigation and water supply for remote and rural communities by stand-alone photovoltaic power supply systems represent an important area, where these systems usually consists of a photovoltaic array, source of water, water tank storage, and a submersible pump as shown in Fig. 1.

The water storage tank in the photovoltaic water pumping system played the role of batteries and the electric power load demand is now replaced by water demand. This electric power load demand represents the energy need to pump the required volume of water demanded by the user into the storage tank. So, the photovoltaic pumping systems can be sized in a similar way than the photovoltaic systems with other applications [4].

The daily water consumption of the station is 45 m^3/day (we will consider that it is same for all the days in the year). Water is pumped by the submersible pump from the groundwater well to two storage tanks of 55 m^3 capacity each, and the station and Bedouin and their livestock's water consumption is supplied from these two water tanks.

4. Renewable resources

In sunny parts of the world, stand-alone photovoltaic systems are becoming cost-effective for the rural and remote applications, such as electrification of widely scattered homes and villages and pumping water. For the majority of the population living in remote, rural and isolated locations, stand-alone photovoltaic systems can be considered as a promising option and a very reliable power source, with minimum attention and maintenance. Demanded load supply with a minimum cost by a photovoltaic installation is a complex problem in which many parameters must be taken into account, such as climatic data, components cost, and the distribution of the load [27–30]. Renewable resources vary enormously from one location to another. The

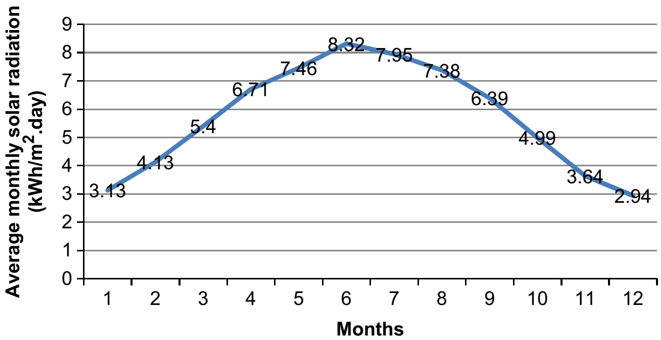

Fig. 2. Monthly average values of solar radiation incident on the horizontal surfaces in Tall Hassan station.

solar resource depends strongly on the latitude and climate. In order to design a cost-minimizing power supply system, we need to consider the available solar resources in the project area [31]. The weather resource affects a renewable system performance and therefore the size of the components. A low resource would result in a larger size system for the same load demand pattern, therefore, the solar radiation is crucial for the photovoltaic power output, [32]. Jordan Badia is known as having a high solar energy, where, utilizing solar energy would be feasible since the daily average of solar radiation on horizontal surface was measured to be 5.3 kWh/m^2/day, while the total annual sunshine hours amount to about 3300 [33]. These figures are very encouraging in terms of using photovoltaic generators for pumping water in Jordan Badia.

Northern Badia is one of the most solar radiated sites in Jordan. A monthly average solar radiation data for Tall Hassan station have been obtained from the Jordan Meteorological Department in Jordan. This is an average of 9 years. Fig. 2 shows the average monthly solar radiation for Tall Hassan station.

It is clear from the figure that solar energy incident in this region is high especially during summer months, where it exceeds 8 and 7 kWh/m^2/day on horizontal surfaces. For example, from Fig. 2 the data vary from 2.94 kWh/m^2/day in December to 8.32 kWh/m^2/day in June. This means that as the demanded load for water increases in summer months, so will the solar resources become high and will meet the demand load of water for the local communities, which is nomadic Bedouin with their animals as well as the demand for the station.

5. Photovoltaic system sizing and components

The first requirement is to determine the amount of water needed. If the water needs vary throughout the year, one has to be conservative and use the highest amount that one expects to use. Meanwhile, the selected site of the water source must then be evaluated for suitability for solar radiation of the photovoltaic water pumping system. The photovoltaic system is sized on the basis of the meteorological and climate data of the location. The key factors required for the photovoltaic water pumping system are water source capacity, water volume required, solar radiation availability, pumping time, static water level, drawdown level, discharge head and pumping subsystem efficiency. Once you have the above information, you need to calculate the most important factor, the total dynamic head (TDH), which is the sum of the static lift of the water, the static height of the storage tank and the equivalent head caused by friction losses in the pipe [26,34].

The photovoltaic pump components must be selected carefully for a proper matching of the system. System design, especially the photovoltaic array capacity, should be reviewed to insure that sufficient energy is produced to start the motor as early in the day as possible. The calculation process has been developed for sizing the photovoltaic water pumping system for any water head, daily demand of water required and hours of operation. The size of the elements and equipments of the photovoltaic water pumping system are computed from the input data. The cost of each part or item will be obtained. The application calculates the total initial investment required by the project and estimates the operation and maintenance cost of the items and equipments. The updated costs for the lifetime of the project are obtained and this tool is used to find the differences of this value between every type of project, besides other indicators like the annual equivalent cost, and the cost per m^3 of water pumped [5].

5.1. Hydraulic sizing

For hydraulic sizing, the user introduces the essential data such as daily water volume required, total pumping head, number of pumping hours per day, material of the pipe grade, length of the pipe, nominal pressure and efficiency of the pump, then the size of the pump and the hydraulic system is calculated according to the following equation [5]:

$$P = \frac{\rho g(h+\Delta H)Q}{\eta_b \eta_e} \tag{1}$$

where P is the pumping power in W; ρ is the density of water in kg/m^3; g is the local acceleration due to gravity, 9.81 m/s^2; h is the total pumping head in m; ΔH is the hydraulic losses in m; Q is the volume of flow in m^3/s; η_b is the efficiency of the pump and η_e is the efficiency of the electric motor.

The hydraulic energy required (kWh/day) is given by [34,35]

$$\begin{aligned} E_h &= \eta_s E_c \\ &= \text{volume required (m}^3\text{/day)} \times \text{head } (m) \times \text{water density} \\ &\quad \times \text{gravity}/(3.6\times 10^6) \\ &= \rho g h V/\,(3.6\times 106) \\ &= 0.002725 \times \text{volume (m}^3\text{/day)} \times \text{head } (m) \end{aligned} \tag{2}$$

where η_s is the subsystem efficiency and V is the daily amount of water required (m^3).

5.2. Photovoltaic system sizing

The two most important factors in the operation of a photovoltaic pump are the availability of sufficient solar radiation to enable the pump to start and the non-linear relationship between the pumping rate and the solar radiation [34].

Photovoltaic stand-alone water pumping systems sizing involves finding the cheapest combination of array size and storage tank that will meet the anticipated load demand requirements with the minimum acceptable level of security [36–38].

Now after the total lift in terms of total dynamic head (TDH) and the pumping rate required are known, one needs to determine the specific pump and the size of the photovoltaic array. The photovoltaic array will be specified in terms of wattage and voltage. It is the standard procedure to increase the specified wattage by 25% (multiply by 1.25) to compensate for power losses due to high heat, dust, aging, etc. [26].

The application sizes of the stand-alone photovoltaic system apply the well known "average case scenario method" and it computes a detailed budget of investment considering the main necessary elements like the photovoltaic modules, inverters, fixed structures, storage tank, wiring and protections [5].

The relationship between the photovoltaic array power and solar radiation energy is [34]

$$P = A_{pv} G_r \eta_r \tag{3}$$

where P is the photovoltaic array power in Wp; A_{pv} is the effective area of the photovoltaic array in m^2; G_r is the solar radiation at reference temperature=1000 W/m^2; η_r is the efficiency of the photovoltaic array at reference temperature (25 C°).

Eq. (3) can be rewritten as

$$P = 1000 A_{pv}\eta_r \quad (4)$$

The effective photovoltaic array area is calculated from the relationship of the daily energy output E_E and the daily hydraulic energy E_h in kWh [34]:

$$E_E = A_{pv} G_T \eta_{pv} \quad (5)$$

where G_T is the daily solar radiation on the photovoltaic array surface (kWh/m^2), and η_{pv} is the efficiency of the photovoltaic array under operating conditions.

The photovoltaic array area can be calculated from Eqs. (2) and (5). Thus

$$A_{pv} = \frac{\rho g h V}{G_T \eta_{pv} \eta_s} \quad (6)$$

By substituting Eq. (6) into Eq. (4), the photovoltaic array size in terms of hydraulic energy and solar radiation energy will be [5,34,35,39]

$$P = 1000 \frac{\rho g h V \eta_r}{G_T \eta_{pv} \eta_s} \quad (7)$$

Eq. (7) can be rewritten as, the solar array power required (kWp)

$$= \frac{Hydraulic\ energy\ required\ (kWh/day)}{Average\ daily\ solar\ iiradiation\ (kWh/m^2/day) \times F \times E} \quad (8)$$

where F is the array mismatch factor, that is, the ratio of the power output of the photovoltaic array under operating conditions to its power output at the maximum power point. The generally accepted value for designing of a photovoltaic system is (0.85–0.90) on average, and E is the daily subsystem efficiency= 0.2–0.6 typically [34,35].

The overall efficiency of the photovoltaic water pump can be determined from the hydraulic energy and from the solar radiation energy input P_{in} as follows [34]:

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h V}{A_{pv} G_T} \quad (9)$$

5.3. Design example

Jordan government through Royal Scientific Society and later through National Energy Research Center is beginning to supply photovoltaic power to the local communities in the remote and rural areas in Jordan Badia who need to pump water for livestock since 1985, and there are about 21 photovoltaic pumping system through the area totaling 101.553 KW peak.

The conventional method of service was to extend the grid line to the isolated areas well even though the income from the customer could never pay for the maintenance of the line. This example is of Tall Hassan station that requires about 45 m^3/day.

From climate and hydrological data of the site in Section 2.2 and Eq. (2), the hydraulic energy required for pumping water is

$$E_h = 0.002725 \times 45 \times 105 = 12.875\ \text{kWh/day}$$

By substituting in Eq. (8), and assuming F=0.9, the array mismatch factor and E=0.5, the daily subsystem efficiency, the solar array power required (kWp) is

$$P = \frac{12.875}{5.7 \times 0.9 \times 0.5} = 5.02\ \text{kWp}$$

We assume a factor of safety 1.2, to compensate for power losses due to high heat, dust, aging, etc., then the solar array power required is

$$P = 1.2 \times 5.02 = 6.0\ \text{kWp}$$

6. Results and discussion

6.1. Case study

The recommended methodology has been applied to analyze a stand-alone photovoltaic water pumping system, which is designed to supply water for drinking the nomadic Bedouin, watering their sheep, goats and camels and irrigation and domestic uses in Tall Hassan station, Northern Badia, Jordan.

The photovoltaic water pumping system was installed in Tall Hassan station and it consisted of a photovoltaic generator, a DC/AC inverter, a pump and a water storage tank. The technical characteristics of the photovoltaic modules, inverter and motor pump used in the studied project are listed in Tables 1–3.

The photovoltaic generator consists of 108 module type SM55 manufactured by Siemens Solar—Germany, with a total peak of 5.94 kW.

The DC/AC inverter is a Simovert manufactured by Siemens Solar—Germany, with rated power of 7.5 KVA.

The pump used in this system is SP8A-37 manufactured by GRUNDFOS—Denmark, with rated motor power of 5.5 kW.

All photovoltaic water pumping systems use some type of water storage. The idea is to store water than electricity in batteries, therefore, reducing the cost and complexity of the system. A general rule is to size a storage tank to hold at least two to three days worth of water.

The water storage system consists of two tanks with a total storage capacity of 110 m^3. This system is designed to supply the villagers, the Bedouins and their herds with about 45 m^3/day of water [4,25,26].

Diesel generators are commonly used for water pumping. In order to analyze the diesel engine solution, we need to size and choose the diesel generator that is able to supply electrical energy

Table 1
Photovoltaic generator specifications.

No. of modules	108
Module area	0.38 m^2
Total modules area	40.8 m^2
Efficiency	13.5%

Table 2
DC/AC inverter specifications.

Input voltage	220 V (DC)
Output voltage	220/380 V (AC, 3 phase)
Rated power	7.5 KVA
Frequency	50 Hz
Efficiency	90%

Table 3
Motor pump specifications.

Type	Submersible
Head	96 m
Rated motor power	5.5 kW
Flow	8 m^3/h
Output voltage	220/380 V—3 phase

Table 4
Motor pump specifications.

Type	Submersible
Head	70 m
Rated motor power	5.5 kW
Flow	8 m^3/h
Output voltage	220/380 V—3 phase

to the pumping system, also, to estimate the initial investment and yearly operation and maintenance cost. Six cylinders in line turbo engine on diesel fuel and generator (10 kW) were chosen. The submersible pump is manufactured by GRUNDFOS/Denmark with a rated motor power of 5.5 kW. It is operated by diesel generator. Specifications of the pump are shown in Table 4 [5,25].

6.2. *Economic analysis*

Although the advantages of photovoltaic technology are evident, economic analysis a key task for the decision of the best technology is often taken in favor of the competing diesel-powered system. The initial high investment costs of the photovoltaic system are critical in this case [5,39].

However, we notice that after the installation the photovoltaic water pumping system requires only a fraction of the operation and maintenance costs of the diesel pumps. For any technology analyzed the tool calculates the total life cycle cost (present value cost, PVC) as shown in Eq. (10). This represents the initial investment cost, operation and maintenance costs along its lifetime. This method allows the comparison of the two alternatives pumping systems and it can analyze economic results with the evolution of variables and its sensitivity [5,34,39].

$$\mathrm{PVC} = I + \sum_{n=1}^{N} \frac{C_n}{(1+r)^n} \tag{10}$$

where C_n is the annual costs, I is the initial investment, N is the period of years and r is the discount rate.

To calculate the present value cost, the annual costs of the system items throughout the lifetime of the system considered in the study are made.

The Annual Equivalent Cost (AEC), is a very useful economic indicator in order to evaluate projects when the present value cost for different alternative technologies is equal or similar. The AEC can be obtained by the following equation [5]:

$$\mathrm{AEC} = \mathrm{PVC}\frac{r(1+r)^n}{(1+r)^n - 1} \tag{11}$$

where AEC is the annual equivalent cost, PVC is the present value cost, n is the period of years and r is the discount rate.

From the annual equivalent cost, the equivalent cost per m^3 or the specific water discharge costs (US\$/m^3) covering both investment and operating costs, taken as a basis for comparing the costs of photovoltaic and diesel water pumping systems, are also obtained. Meanwhile, the specific water discharge costs permit an evaluation of different pumping technologies, even for sites involving different pumping heads and degrees of utilization [5,39].

For the present photovoltaic water pumping system, the present value cost will be estimated as follows. The system life span (n) components estimated is 25 years, the same as the life span expected for the photovoltaic panels. Also, the annual inflation rate will be considered 0% and the nominal market discount rate (r) as 10% [23,40].

The initial cost of the photovoltaic water pumping system including the PV array, inverter, submersible pump, pipes and auxiliaries is (I)=20,790 US\$.

Also, the annual maintenance and operation cost is about 2% of the initial cost [23,29].

$$\text{O and M cost} = 0.02 \times \mathrm{I} = 0.02 \times 20{,}790 = 416\ \text{US\$}$$
$$\text{Annual cost} = C_n = 416\ \text{US\$}$$

By applying Eq. (10), the present value cost is

$$\mathrm{PVC} = 20{,}790 + \sum_{n=1}^{25} \frac{416}{(1+0.1)^{25}} = 24{,}566\ \text{US\$}$$

By substituting in Eq. (11), the annual equivalent cost is

$$\mathrm{AEC} = 24{,}566 \frac{0.1(1+0.1)^{25}}{(1+0.1)^{25} - 1} = 2706.4\ \text{US\$}$$

The equivalent cost per m^3 or the specific water discharge costs (US\$/m^3) is

$$\text{Specific water discharge cost} = \frac{2706}{13{,}392} = 0.2\ \text{US\$/m}^3$$

where 13,392 m^3 is the annual pumping water quantity.

In order to estimate the present value cost of the diesel generator, we assume the following: a single diesel generator will be used, with a power capacity of 10 kW; the operation, maintenance and oil changing costs are about 5% of the initial prices [23]; fuel consumption is about 25 l/day for 6 h of operation daily to pump the required quantity of water, which is 45 m^3 [25].

For larger units per kW cost is lower and for smaller units cost is more. Since the peak power demand is less than 6 kW, in this analysis diesel generator cost is 4500 US\$ [25]. At present, in Jordan, diesel price is around 0.78 US\$/l.

$$\text{Initial cost} = I = 1 \times 4500\ \text{US\$/unit} = 4500\ \text{US\$}$$
$$A = \text{first year fuel cost} = 25\ \text{l/day} \times 365 \times 0.78\ \text{US\$/l} = 7117.5\ \text{US\$}$$

Operation, maintenance and oil changing costs $= 0.05 \times I = 0.05 \times 7117.5 = 225$ US\$.

$$\text{Annual cost} = C_n = 7117.5 + 225 = 7342.5\ \text{US\$}$$

By substituting in Eq. (10), the present value cost is

$$\mathrm{PVC} = 4500 + \sum_{n=1}^{25} \frac{7342.5}{(1+0.1)^{25}} = 71{,}148\ \text{US\$}$$

By applying Eq. (11), the annual equivalent cost is

$$\mathrm{AEC} = 71{,}148 \frac{0.1(1+0.1)^{25}}{(1+0.1)^{25} - 1} = 7826.3\ \text{US\$}$$

The equivalent cost per m^3 or the specific water discharge costs (US\$/m^3) is

$$\text{Specific water discharge cost} = \frac{7826.3}{13{,}392} = 0.58\ \text{US\$/m}^3$$

7. Evaluation of the deep well in Tall Hassan station area

In the remote areas where the grid extension is not feasible, the only possible choice is to power the water pumping systems with photovoltaic systems or with diesel engines. In addition, it is very interesting to analyze which of these two systems is better from an economical point of view [5].

In the station there are two systems for water pumping, photovoltaic array and diesel engine. Table 5 shows the main indicators of the two options evaluated to energize the water pumping system. The photovoltaic option is the most profitable economically, with the fuel price of 0.78 US\$/L for the diesel

Table 5
Comparison among photovoltaic and diesel engine pumping systems.

US$	Photovoltaic	Diesel engine
Initial investment	20,790	4500
Operational cost	416	7342.5
Present value cost (PVC)	24,566	71,148
Annual equivalent cost (AEC)	2706.4	7826.3
US$/m^3	0.20	0.58

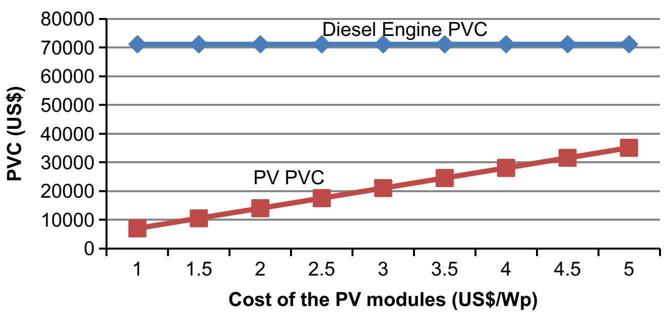

Fig. 3. Sensitivity of the PVC of the projects, with the cost of the PV modules (US$/Wp).

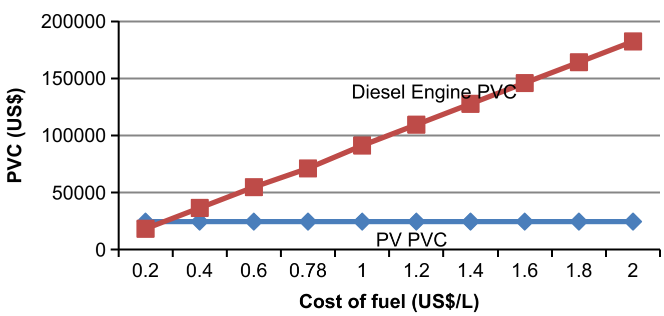

Fig. 4. Sensitivity of the PVC of the projects, with the cost of fuel (US$/L).

engine. All the indicators of the photovoltaic project for this case are lower than those obtained for the diesel engine, except for the initial investment, that is the biggest one.

From Fig. 3, we notice that as the price of the photovoltaic modules lowers, the profitability of the photovoltaic option increases, where the design point is 3.5 US$/Wp. Also, even if the price of the photovoltaic modules increases still they are a suitable option; however the prices of the photovoltaic modules decreased yearly.

Fig. 4 shows the sensitivity of the present value cost (PVC) of the project with diesel engine with the cost of the fuel. It can be observed that when the price of the fuel is lower than 0.78 US$/L, the photovoltaic solution is the most profitable until the fuel price is less than 0.4 US$/L.

8. Conclusions

In this paper we have shown the application of two systems, photovoltaic stand-alone project and diesel generator, to supply the energy for a water pump to feed the water consumption in a remote area in Jordan Badia for a case study. In remote areas with high insolation levels, electricity from solar cells opens up new options for pumping water. Besides that an evaluation guide has been introduced for these systems so as to improve its feasibility. The application developed has been proved as a good tool for obtaining estimates of the initial investment and annual operation of photovoltaic and diesel engines pumping systems in Jordan Badia. It allows to calculate the present value cost, comparing two possible solutions for the same pumping project.

This paper shows that the photovoltaic water pumping systems can be more cost effective than diesel engines to energize pumping systems in Jordan Badia and it is possible to give advice quickly about the most cost effective solution about the same project from an economical point of view in the area.

References

[1] Al-Smairan MH. Investigation of a hybrid wind-photovoltaic electrical energy system for a remote community. PhD thesis. Coventry, UK: Mechanical Engineering Department, Coventry University; 2006.
[2] Dutton R, Shahbaz M. Jordan's Arid Badia: deepening our understanding. Amman, Jordan: Jordan Badia Research and Development Centre; 2008.
[3] Biswas Wahidul K. Application of renewable energy to provide safe water from deep tubewells in rural Bangladesh. Energy for Sustainable Development 2011;15:55–60.
[4] Bakelli Yahia, Hadj Arab Amar, Booubekeur. Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept. Solar Energy 2011;85:288–94.
[5] Chueco-Fernandez Francisco J, Bayod-Rujula Angel A. Power supply for pumping systems in northern Chile: photovoltaic as alternative to grid extension and diesel engines. Energy 2010;35:2909–21.
[6] Mahmoud M, Ibrik I. Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid. Renewable and Sustainable Energy Reviews 2006;10:128–38.
[7] Mousa MA, Ibrahim IMSaleh, Molokhia IM. Comparative study in supplying electrical energy to small remote loads in Libya. Renewable Energy 1998;1–4(14): 135–40.
[8] Bhave AG. Potential for solar water-pumping systems in India. Applied Energy 1994;48:197–200.
[9] Kelley Leah C, Eric Gilbertson, Anwar Sheikh, Eppinger Steven D, Steven Dubowsky. On the feasibility of solar-powered irrigation. Renewable and Sustainable Energy Reviews 2010;14:2669–82.
[10] Kala Meah, Steven Fletcher, Sadrul Ula. Solar photovoltaic water pumping for remote locations. Renewable and Sustainable Energy Reviews 2008;12(2): 472–87.
[11] Hamidat A, Benyoucey B. Systematic procedures for sizing photovoltaic pumping system, using water tank storage. Energy Policy 2009;37(4):1489–501.
[12] Kumar Atul, Kandpal Tara C. Renewable energy technologies for irrigation water pumping in India: A preliminary attempt towards potential estimation. Energy 2007;32(5):861–70.
[13] Hrayshat Eyad S, Al-Soud Mohammad S. Potential of solar energy development for water pumping in Jordan. Renewable Energy 2004;29(8):1393–9.
[14] Ramos JS, Ramos Helena M. Solar powered pumps to supply water for rural or isolated zones: a case study. Energy for Sustainable Development 2009;13(3): 151–8.
[15] Butcher W. Aspects of solar water pumping in remote regions. Energy for Sustainable Development 1996;3(4):8–27.
[16] Mahjoubi A, Mechlouch RF, Ben Brahim A. Economic viability of photovoltaic water pumping systems in the desert of Tunisia. International Renewable Energy Congress; 2010 [November 5–7, 2010, Sousse, Tunisia].
[17] Abu-Aligah M. Design of photovoltaic water pumping system and compare it diesel powered pump. Jordan Journal of Mechanical and Industrial Engineering 2011;5(3):273–80.
[18] Eker B. Solar powered water pumping systems. Trakia Journal of Sciences 2005;3(7):7–11.
[19] Foster R, Cisneros G, Hanley C. Life-cycle cost analysis for photovoltaic water pumping systems in Mexico. In: Proceedings of the second world conference on photovoltaic solar energy conversion. Vienna, Austria; 6–10 July, 1998.
[20] Kordab M. Priority option of photovoltaic systems for water pumping in rural areas in ESCWA member countries. Desalination 2007;209:73–7.
[21] Borowy Bogdan S, Salameh Ziyad M. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/ PV hybrid system. IEEE Transactions on Energy Conversion 1996;11(2):367–73.
[22] Elhadidy MA, Shaahid SM. Parametric study of hybrid (wind+solar+diesel) power generating systems. Renewable Energy 2000;21:129–39.
[23] Ahmed GE. Photovoltaic-powered rural zone family house in Egypt. Renewable Energy 2002;26:379–90.
[24] Elhadidy MA. Performance evaluation of hybrid (wind/solar/diesel) power systems. Renewable Energy 2002;26:401–13.
[25] Jordan Badia Research and Development Center. Tall Hassan renewable energy station, annual report. Amman, Jordan; 2011.
[26] New York State, Energy Research and Development Authority. Guide to solar powered water pumping systems in New York State. Available from: 〈water.epa.gov/infrastructure/sustain/2005_1_27_publication_solarpumpingguide.pdf〉; 2012 [online].
[27] Gordon JM. Optimal sizing of stand-alone photovoltaic solar power systems. Solar Cells 1987;20:295–313.
[28] Hadj Arab A, Ait Driss B, Amimeur R, Lorenzo E. Photovoltaic systems sizing for Algeria. Solar Energy 1995;54(2):99–104.

[29] Markvart Tomas. Solar electricity. Baffins Lane, Chichester, West Sussex PO16 1UD, England: John Wiley and Sons; 1997.
[30] Vallve X, Serrasolses J. Design and operation of a 50 kWp PV rural electrification project for remote sites in Spain. Solar Energy 1997;59(1–3):111–9.
[31] Kamel Sami, Carol Dahl. The economics of hybrid power systems for sustainable desert agriculture in Egypt. Energy 2005;30(8):1271–81.
[32] Protogeropoulos C. Autonomous wind/solar power systems with battery storage. PhD thesis. University of Wales College of Cardiff; 1992.
[33] Jordan Meteorological Department. Internal report. Amman, Jordan; 2011.
[34] Khatib T. Design of photovoltaic water pumping systems at minimum cost for Palestine: a review. Journal of Applied Sciences 2010;10:2773–84.
[35] Practical action, the Schumacher Centre for Technology and Development. Solar (photovoltaic) water pumping, Bourton hall, Bourton-on-Dunsmore. 2012.
[36] Bhuiyan M, Asgar M. Sizing of a stand-alone photovoltaic power system at Dhaka. Renewable Energy 2003;28:929–38.
[37] Samimi J, Soleimani EA, Zabihi MS. Optimal sizing of photovoltaic systems in varied climates. Solar Energy 1997;60(2):97–107.
[38] FSEC. Stand-alone photovoltaic lighting systems, a decision-maker's guide. Available from: 〈http://www.fsec.ucf.edu/PVT/Resources/Publications/pdf/FSEC-RR-54-1998-2pdf〉; 1998 [online].
[39] Hahn A. Photovoltaic water pumping, gate information service/gtz, P.O. Box 5180, 65726 Eschborn, Germany; 2000.
[40] Bernal-Agustín José L, Dufo-López Rodolfo, Domínguez-Navarro José A, Yusta-Loyo José M. Optimal design of a PV-wind system for water pumping. Available from: 〈http://www.icrepq.com/icrepq-08/450-bernal-n.pdf〉; 2012 [online].